

Soil Moisture in the Climate System

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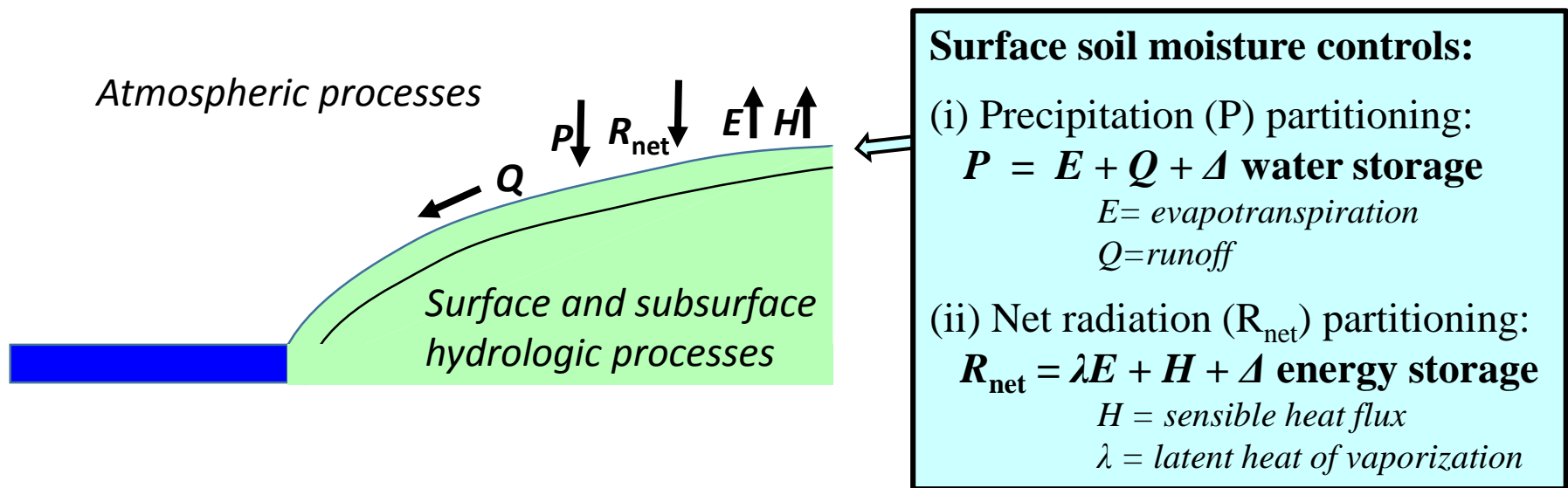
Our Warming Planet: Topics in Climate Dynamics

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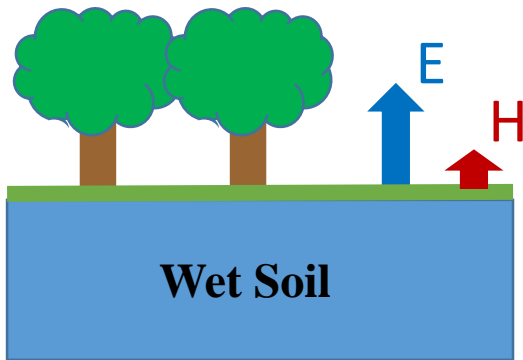
Soil Moisture in the Climate System

The moisture in the top two meters or so of soil is a tiny fraction ($<0.01\%$) of the Earth's water. However, because it lies at the *interface* between the land and atmosphere, it has an *inordinate impact* on climate and its variability.



How Does Soil Moisture Affect Climate Variability?

Through its impact on the surface energy and water balances, as characterized by its impact on evapotranspiration.



For example:

Wet soil \Rightarrow higher evap., lower sensible heat flux

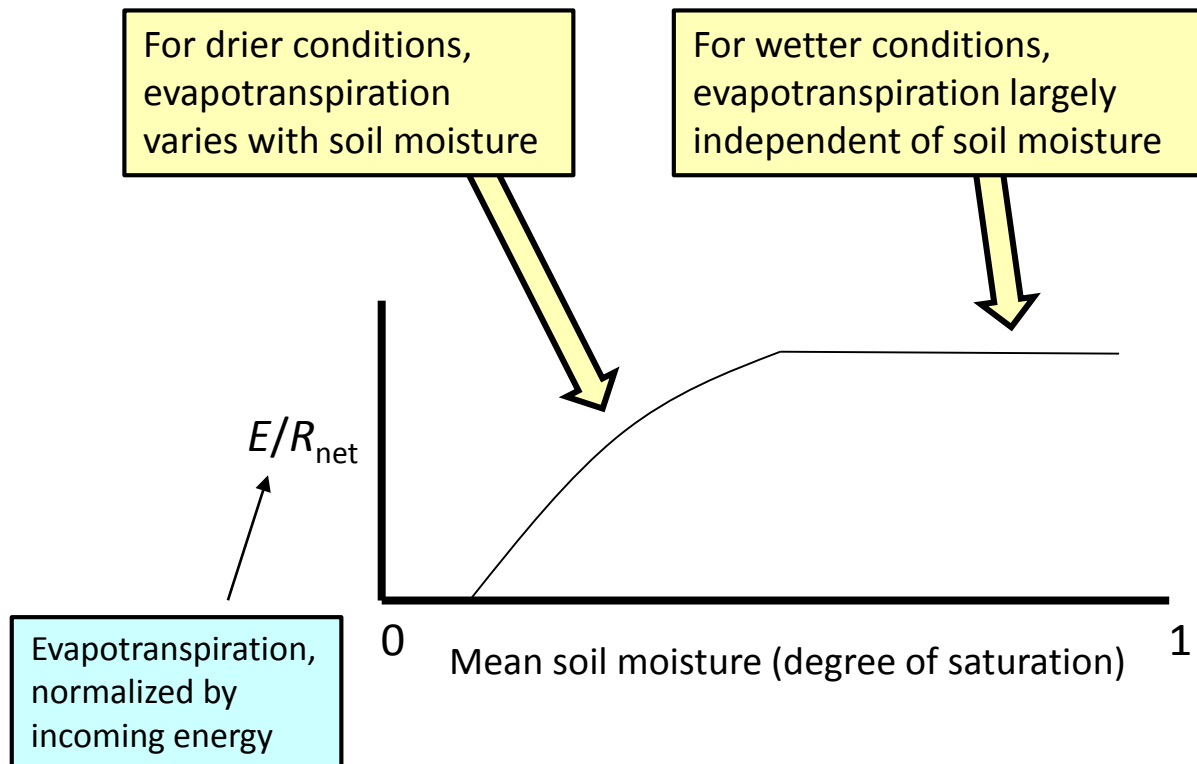
This can affect local air temperature:

- \Rightarrow more evaporative cooling
- \Rightarrow lower air temperature

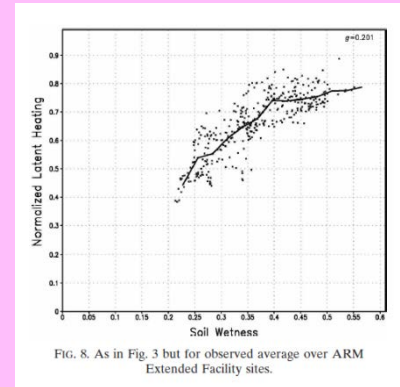
It can also affect local precipitation:

- \Rightarrow boundary layer modification
- \Rightarrow conditions more conducive
(or perhaps less conducive)
to onset of moist convection

Conventional Wisdom Regarding Control of Soil Moisture on Evapotranspiration



Relevant observations are rare, but where they exist, they support this idea....

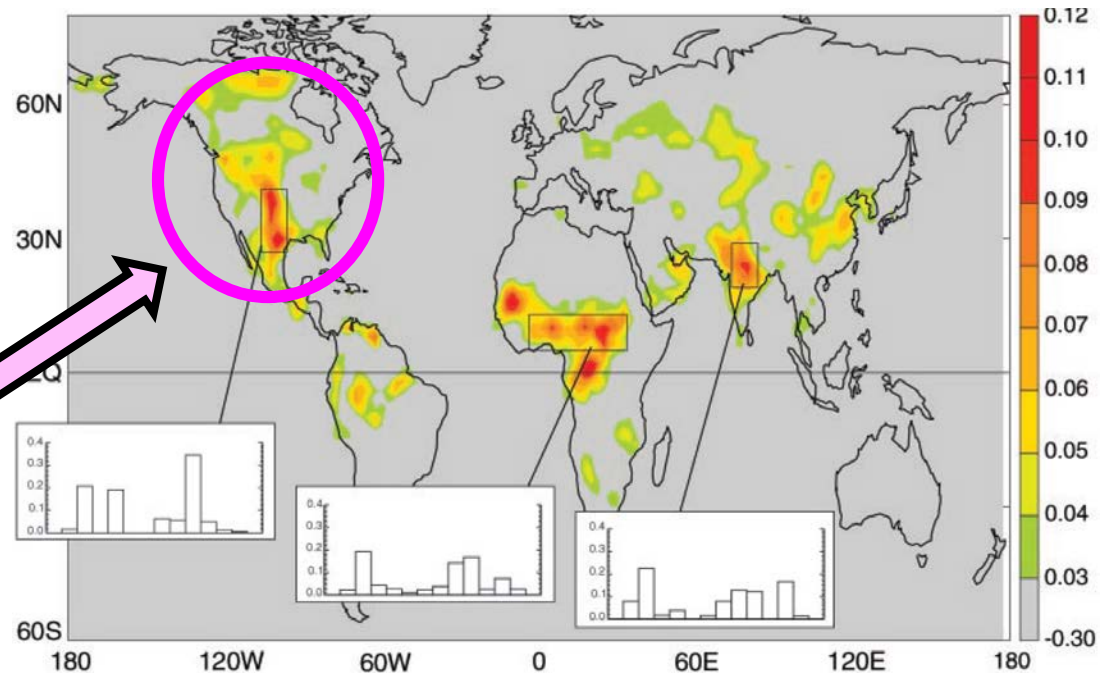


Dirmeyer *et al.*, *J. Hydromet.*, 7, 1177–1198, 2006

Because of this relationship, the connection between soil moisture and the atmosphere (through the former's effect on evapotranspiration) is strongest in the transition zones between dry and wet areas.

Shown here: results from the multi-model GLACE experiment. Indicated is where soil moisture variability helps guide short-term boreal summer rainfall variability.

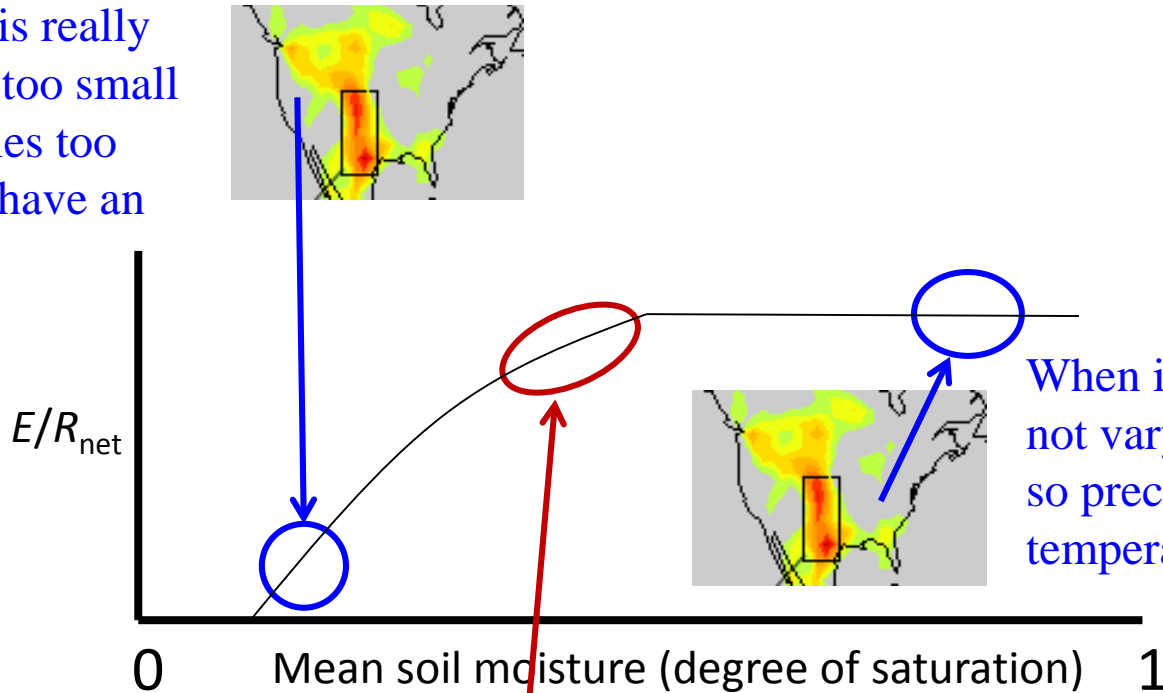
Why are the transition areas important? See next slide, which focuses on North America...



Koster et al., Science, 305, 1138–1140, 2004

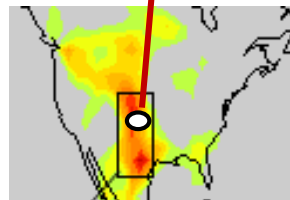
Explanation for Why Soil Moisture Feedback on the Atmosphere is Strongest in Transition Zones

When it is really dry, E is too small (and varies too little) to have an effect.



When it is really wet, E does not vary with soil moisture, so precipitation and temperature cannot, either.

You mainly get an impact in the “sweet spot” in between:

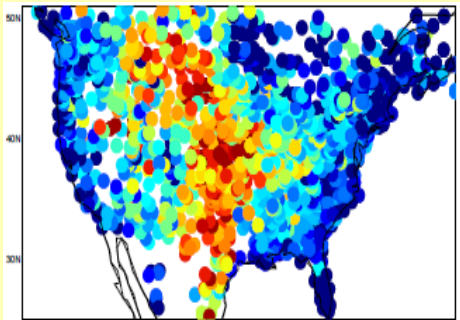


...in the transition zone, where E does vary with soil moisture and E is significantly large.

Direct evapotranspiration measurements are too sparse to show this pattern. However, the pattern is seen in measurements of E-related proxy variables.

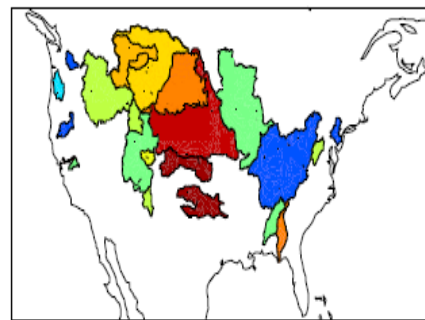
Wanted: indication of where interannual variability of E is large. Plot instead: interannual variability of well-measured variables that vary with E . (Plot $\sigma^2_X \text{Corr}^2(X, W)$, where X is the proxy variable and W characterizes water availability.)

Proxy: JJA air temperature, T



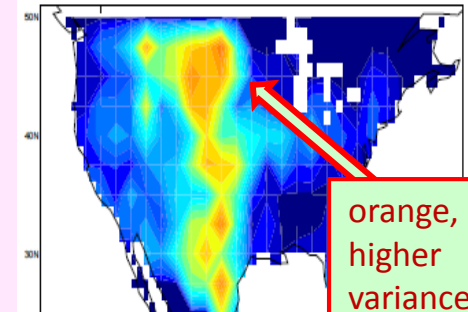
T varies with E : higher E
⇒ more evaporative cooling
⇒ lower T .

Proxy: annual precipitation minus streamflow, $P-Q$



Q varies with E : higher E
⇒ lower Q , from water balance.

Proxy: Aug-Sept NDVI

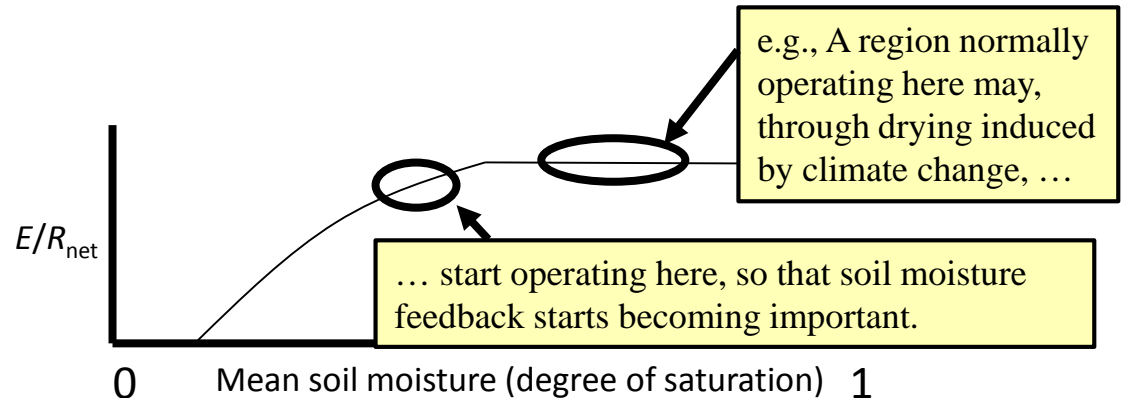


NDVI varies with E :
lower soil moisture
⇒ lower E , lower NDVI.

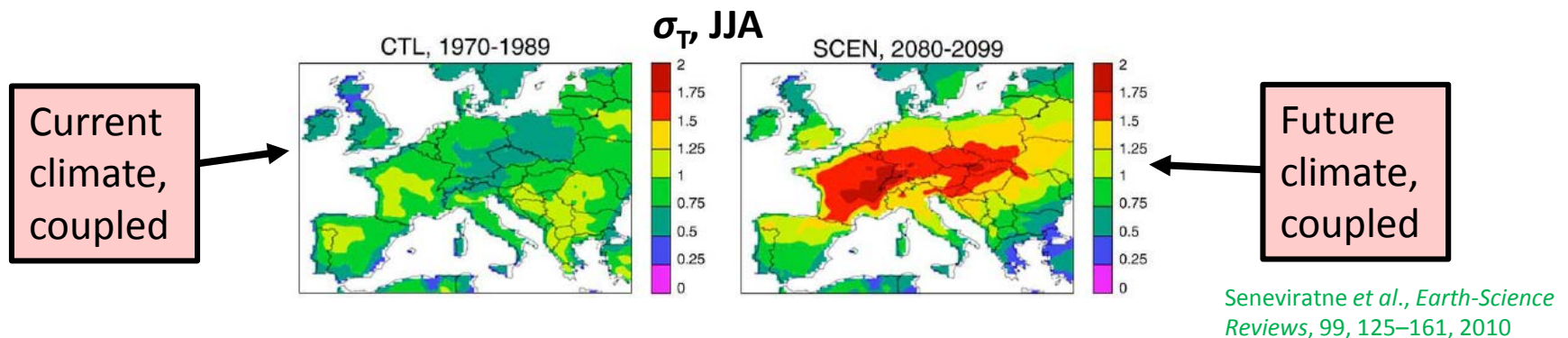
Koster et al., Frontiers in Earth Science, 2015

Soil Moisture in a Changing Climate

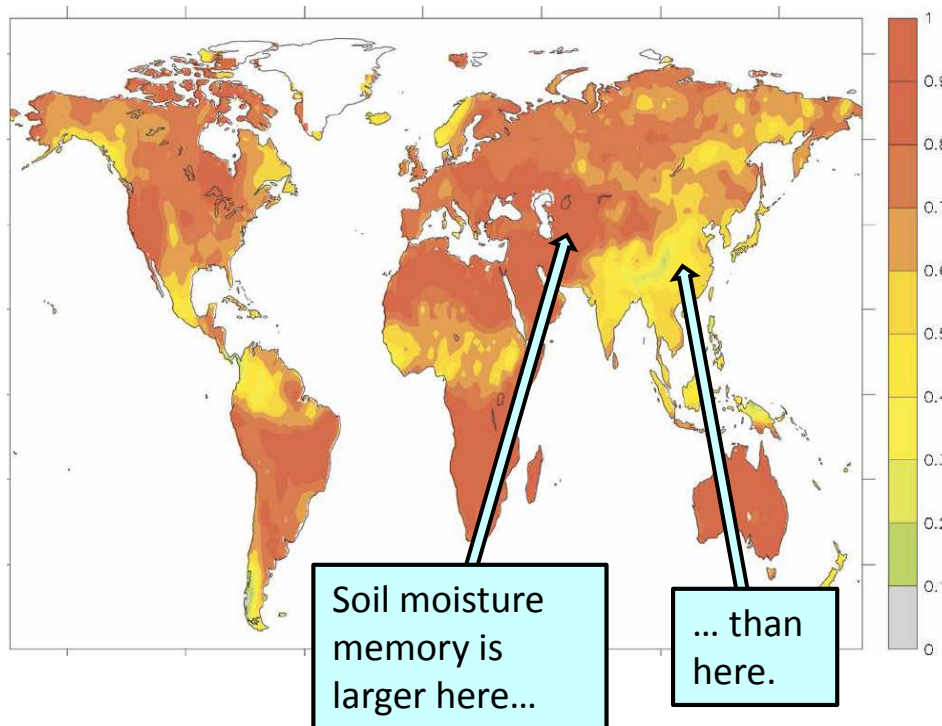
Climate change may lead to a shift in a region's hydroclimatic regime.



Models suggest such a shift in Europe, with soil moisture having a larger impact on climate variability during future climate.



Another relevant property of soil moisture: “memory”. If the soil is anomalously wet today, it will probably be anomalously wet tomorrow, next week, and maybe even next month.

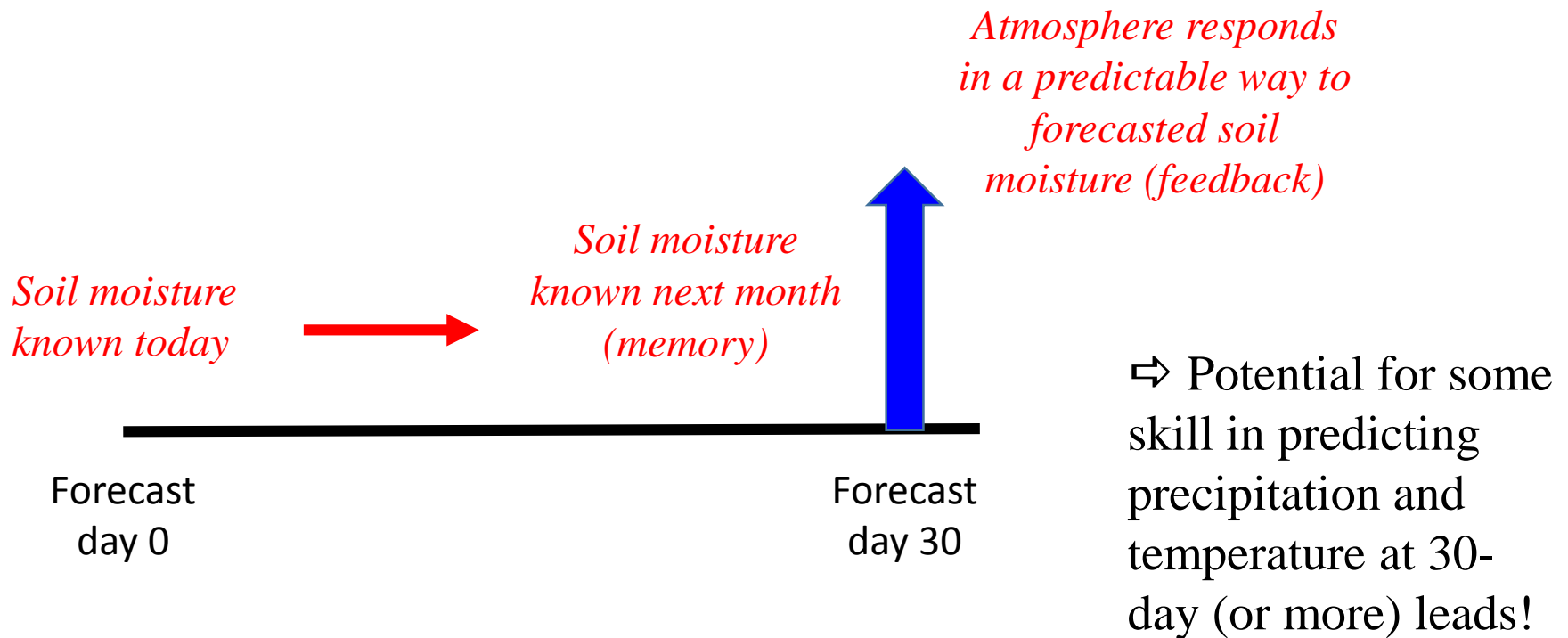


⇐ Multi-model estimate of 27-day-lagged autocorrelation of soil moisture (boreal summer).

Observed estimates for individual locations are sparse, but where they exist, the models roughly agree with them.

Seneviratne et al., J. Hydromet., 7, 1090–1112, 2006

This memory, in combination with soil moisture's ability to feed back on the atmosphere, has an important implication:



Estimations of Forecast Skill Associated with Soil Moisture Initialization

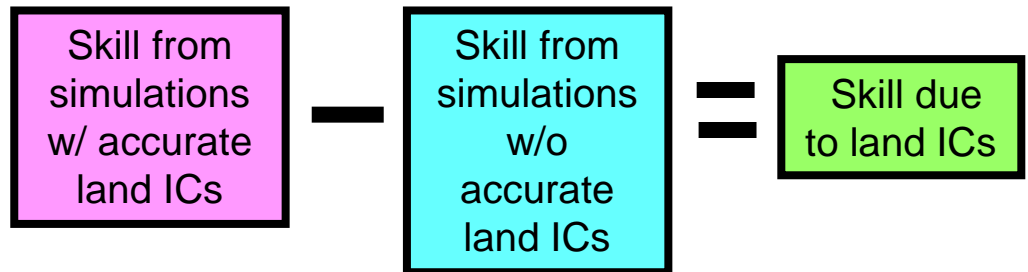


The second phase of the
Global Land-Atmosphere Coupling Experiment
(an international, multi-institution project)

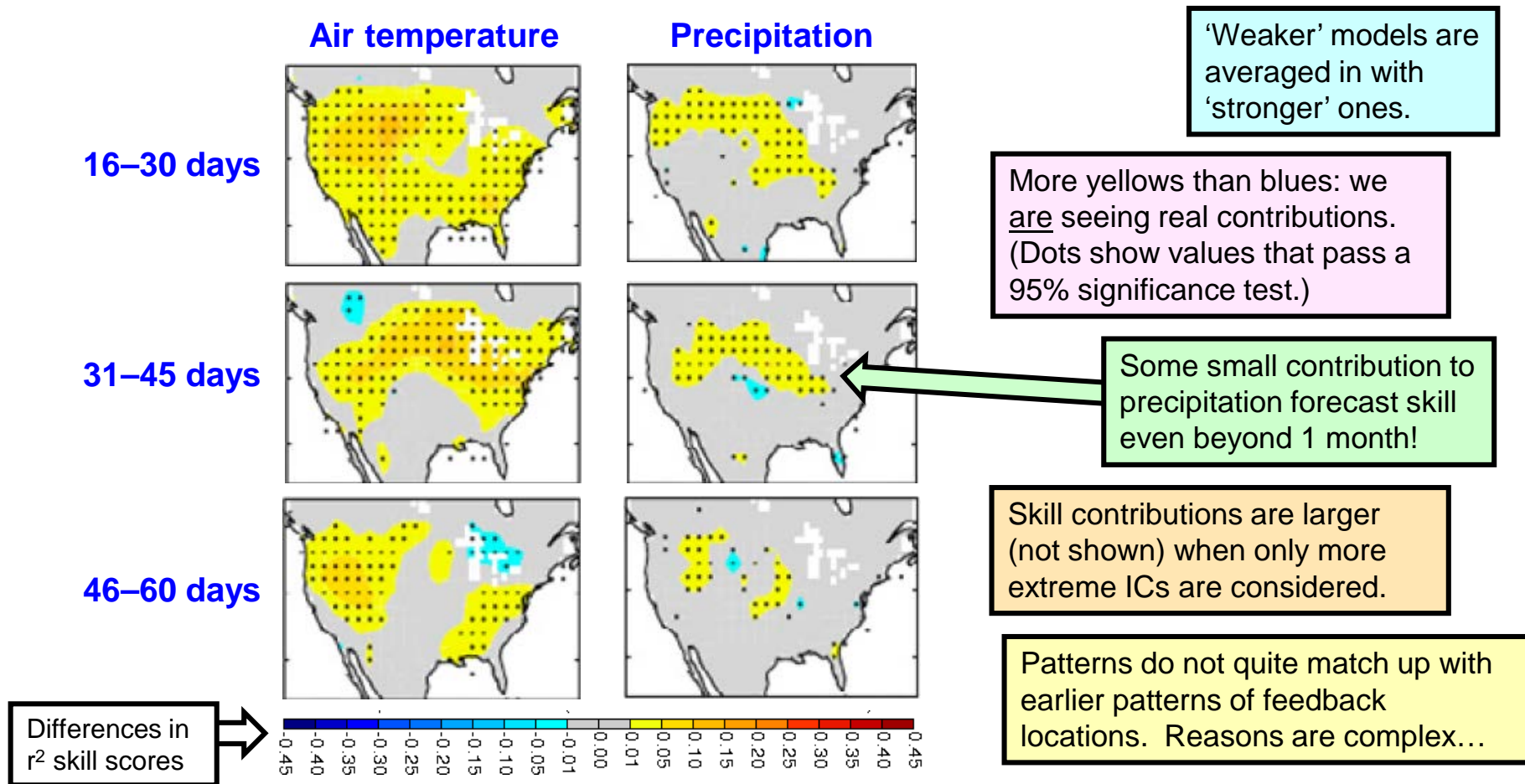
Koster et al., J. Hydromet., 12, 804-822, 2011

Gist of experiment:

1. Perform two sets of forecast simulations:
 - (i) with accurate soil moisture initial conditions (ICs)
 - (ii) without accurate soil moisture ICs
2. Compare forecasted P , T to obs.
3. Compute soil moisture contribution to forecast skill:

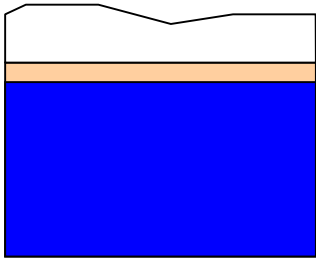


GLACE-2 Results: 'Consensus' Skill Contribution from Land Initialization (JJA)

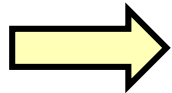
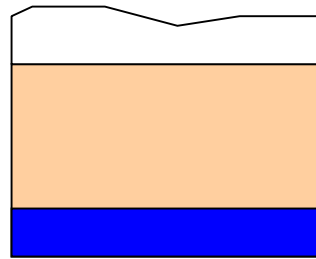


Soil Moisture and Streamflow Forecast Skill

Snow (or rainfall) over wet soil: most of the meltwater runs off into streams, reservoirs.

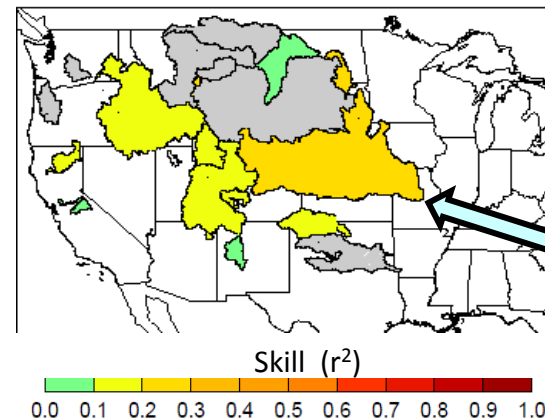


Snow (or rainfall) over dry soil: much of the meltwater infiltrates the soil and is lost to evapotranspiration \Rightarrow less to streams, reservoirs.



Knowledge of winter soil moisture, coupled with soil moisture memory, provides springtime streamflow forecast skill.

Forecast experiment: compute skill of March–July streamflow forecasts (vs. obs) associated solely with accurate soil moisture initialization:



Real skill found in many basins!

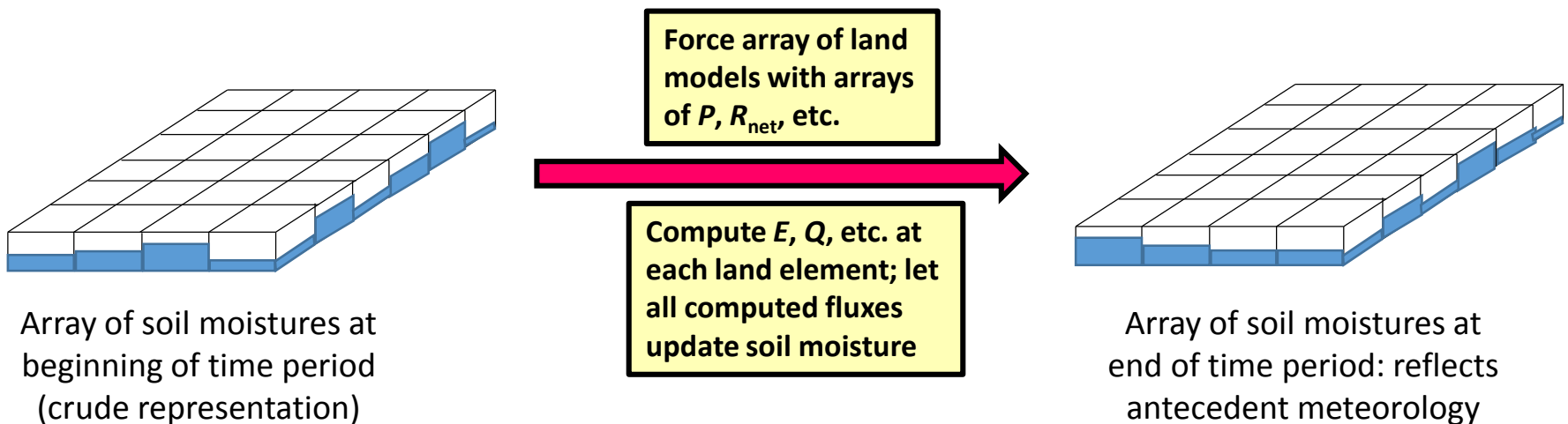
Koster et al., Nature Geoscience, 3, 613–616, 2010.

Soil Moisture in Earth System Models

How can we initialize soil moisture, e.g., for forecasts? From direct, in situ observations?

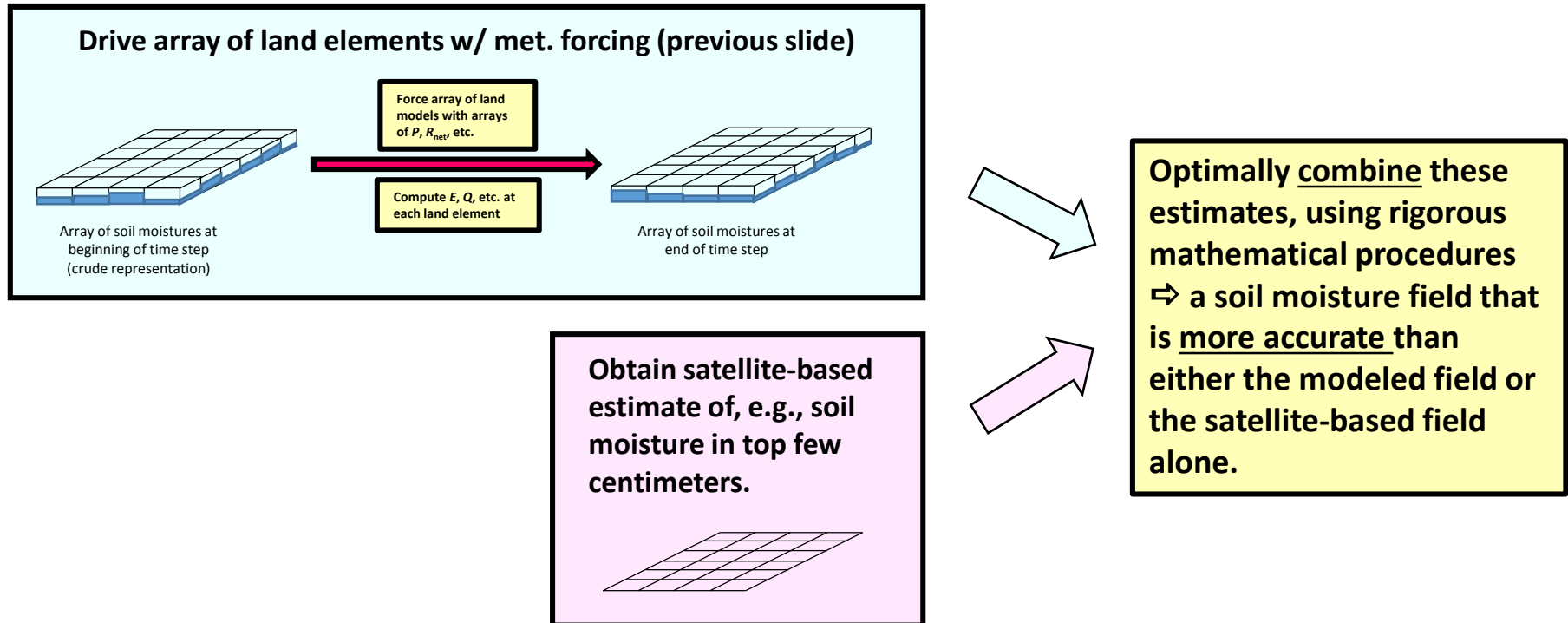
No. *In situ observations (certainly across large areas) are sparse to non-existent.*

Modeling approach: Force a gridded array of land surface model elements with arrays of observations-based meteorological forcing \Rightarrow let modeled soil moistures evolve in response to the forcing.



Soil Moisture in Earth System Models

Even better approach: Combine modeling and observations through data assimilation:



Soil Moisture in Earth System Models

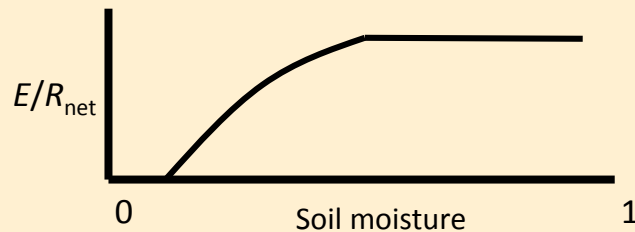
New satellite-based L-band sensors have the potential to provide valuable global soil moisture data \Rightarrow A renaissance in soil moisture estimation through assimilation?



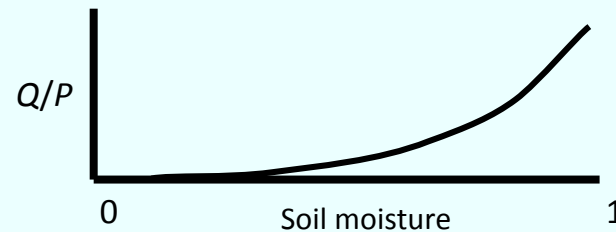
Spatial resolution : 36-km
Temporal resolution : every 3 days (at least)
How deep into soil: several cm (Level 1–3)
1 m (Level 4)
Accuracy: RMSE < 4 volumetric percent
Latency: short! (hours – days)
Baseline mission duration: 3 years

Soil Moisture in Earth System Models: Some Caveats

As discussed earlier, evapotranspiration is controlled by soil moisture.

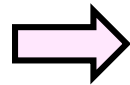


Similarly, the ratio of runoff to precipitation is controlled by soil moisture.



A land surface model has multiple complex formulations that interact with each other, implicitly producing some form of these two relationships (approximate—scatter will be large around them).

It is the **interaction** between these underlying relationships that determines how a land surface model behaves.



Important Modeling Take-home Lesson:

A 'perfect' evapotranspiration formulation does not imply accurate evapotranspiration rates. Accuracy in E is limited by the weaker of the evapotranspiration and runoff formulations. Model development requires suitable **balance**.

Koster and Mahanama, *J. Hydromet.*, 13, 1604–1620, 2012.

Koster, *Bull. Am. Met. Soc.*, 96, 393–396.

Also, soil moisture in a land surface model is a very model-dependent variable, more an ‘index of wetness’ than an actual physical quantity.

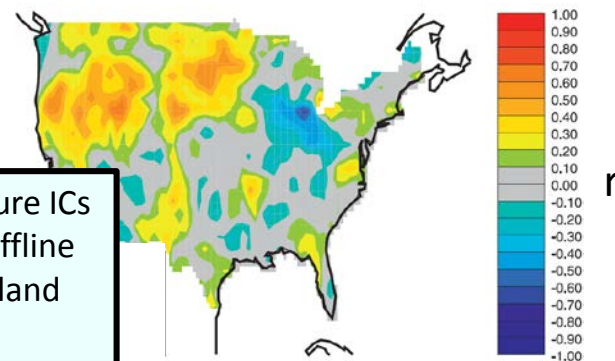


Another Important Modeling Take-home Lesson:

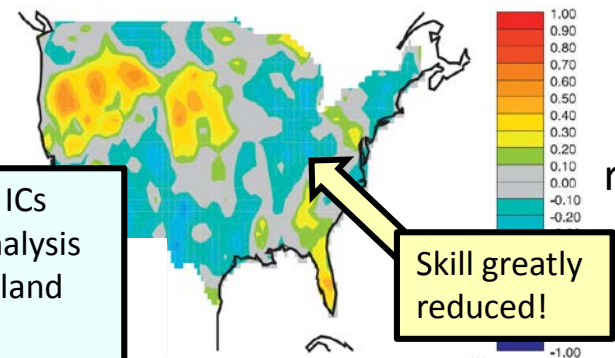
Taking soil moisture from one model (e.g., from a reanalysis) and using it in another can lead to serious problems. Scaling is essential.

Demonstration of problem: seasonal precipitation forecast skill

Using soil moisture ICs obtained from offline system w/same land surface model.



Using soil moisture ICs obtained from reanalysis that used different land surface model.



Koster *et al.*, *J. Climate*, 22, 4322–4335, 2009.

A Few Summary Statements

Variability in near-surface soil moisture can causally translate to variability in meteorological variables through the influence of soil moisture on the energy and water budgets at the land-atmosphere interface, particularly in transition zones.

This potential for feedback, combined with soil moisture's intrinsic memory, provides the basis for utilizing soil moisture information in monthly-to-seasonal forecasts.

The outlook for improved soil moisture estimation (e.g., for initializing forecasts) is optimistic given the advent of new satellite data, which can be assimilated into land surface models. Use of models, however, comes with important caveats:

- A model's overall performance is only as good as the weaker of its evapotranspiration and runoff formulations (not often appreciated!)
- Inserting soil moisture from one model (even from a trusted reanalysis) into another without performing climatology transformations can lead to significant problems (appreciated even less!)